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FINAL TECHNICAL REPORT FOR NAGW-2479

Submitted to:

Dr. Guenter Riegler
Code SR, Room 4E82
NASA Headquarters
Two Independence Square
300 East Street, SW
Wahsington, DC 20546

Submitted by:

The Trustees of Columbia University
in the City of New York
351 Eng. Terrace
New York, New York 10027

Prepared by:

Columbia Astrophysics Laboratory
Departments of Astronomy and Physics
Columbia University
558 West 120^{th} Street, MC-5247
New York, New York 10027

Principal Investigator:

R. Michael Rich

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Final Technical Report for NAGW-2479

"Ages and Abundances of Bulge Populations"

R. Michael Rich, Principal Investigator

The Long Term Space Astrophysics Grant "Ages and Abundances of Bulge Populations" addressed the following questions:

1. Are there any luminous, intermediate-age stars in Local Group bulge populations?

To answer this question, the PI pursued a ground based program to image bulges in the infrared, and a program using the Hubble Space Telescope (HST) to image bulges using the WFPC and WFPC2. Initial infrared imaging from Palomar (Rich & Mould 1991) gave indications of an excess of giants with $M_{bol} < -4$ (brighter than the He flash). Subsequently, there were some concerns that the fields observed could be contaminated by disk stars. Rich, Mould, & Graham (1993) imaged 5 fields in M31 with varying amounts of disk and bulge light. This effort showed that the excess of bright stars could not be due to disk contamination, and found indications for a striking excess of luminous giants in the inner 2 arcmin of M31. There remains concern that the ground-based data was affected by photometric crowding. The PI has proposed to use NICMOS and HST to finally settle this issue. However, within the context of the LTSA proposal, the PI undertook a number of HST efforts to settle the question. Using WFPC (and pre-repair data; GO-2735) the PI imaged the nucleus of M31 and used careful crowded field aperture photometry techniques (and artificial star tests), finding an excess of bright stars in the Johnson I band (Rich & Mighell, 1995). This was a curious result because metal rich giants should be found at a relatively faint $M_I = -2$, whereas these stars are at $I = 19$, or $M_I = -5$. The PI also found these stars to be centrally concentrated, apparently confirming and extending earlier ground-based work done by Mould. The effort to investigate evolved stars in bulges was more successfully applied to M33 (Mighell & Rich, 1995), where WFPC focused on the central 100 pc of M33. The stellar population was clearly resolved into young stars,

stars on globular cluster giant branches with a wide range in metallicity, and stars that appeared to belong to an extended giant branch/AGB population with $M_I < -4$. The latter population was more centrally concentrated than the old, globular cluster like stars at $> 99\%$ level of significance. The differing spatial distributions of the apparently old and intermediate-aged stars is striking, and further study has been pursued in Rich's subsequent HST observations. The Cycle 4 program GO 5464 imaged the central regions of M31, M32, and M33. Some indication has been found for an extended giant branch in the F1042M band. However, the PI has been pursuing very careful artificial star addition tests on these data, and no firm conclusions can be drawn at this time.

In summary, there is some evidence that an unexplained popualation of bright AGB stars is present in Local Group bulges. It is possible that these correspond to the luminous $M_{bol} < -5$, long period Miras in the Milky Way bulge. However, there appear to be few progenitor turnoff stars with intermediate age. A detailed comparison of the luminosity functions of old metal rich globular clusters in the Galactic bulge with the field population luminosity function limits the age dispersion to $< 10\%$ of the turnoff stars (Ortolani et al. 1995). The PI combined ground-based imaging of the Galactic bulge with HST-based imaging of the globular clusters. This first effort will be followed on in other bulge fields.

2. What is the abundance range and chemistry of the bulge?

The most significant outcome of this LTSA grant was the high dispersion abundance analysis of CTIO spectra by McWilliam & Rich (1994). The following results obtained: 1. The low resolution [Fe/H] scale for bulge giants was shown to be incorrect, and the mean [Fe/H] was reduced by 0.25 dex to -0.15 dex. The bulge population was therefore shown to have approximately Solar [Fe/H]. 2. The alpha-capture elements Mg and Ti are enhanced in the bulge, but Ca and Si (also alpha-capture) follow the normal disk enrichment trend. There is no known class of SNe that can produce such a curious enrichment pattern. 3. s-process elements, which are produced in the He-burning shells of AGB stars, have Solar abundance in bulge stars. The wide range of abundances in bulge giants found by Rich (1988) was confirmed by this work. Neil Tyson's (1991) Ph.D. thesis addressed the

abundance gradient of the Galactic bulge, using Washington photometry. This work also confirmed the wide range of abundances in other bulge fields.

3. What is the cause of the ultraviolet rising flux in ellipticals and bulges?

On this question, the project was not so successful. Rich, Minniti, & Liebert (1993) imaged 6 metal rich globular clusters with the International Ultraviolet Explorer (IUE) satellite. An unexplained source of far ultraviolet flux is present in elliptical galaxies and some bulges. It appears to be correlated with Mg line strength (a measure of metallicity). In order to find the stars responsible for this radiation, thePI emaphsized the study of the nearby metal rich clusters and the Galactic bulge, with follow-on by HST. Two clusters, NGC 6388 and 6441, were well detected by IUE and have [Fe/H]=−0.6, much too high to have any blue horizontal branch stars. The PI imaged NGC 6388 with the Faint Object Camera and found a curious UV bright population. Only with WFPC2 (after the expiration of the LTSA) was the extraordinary hot blue HB discovered (Rich et al. 1997). However, the ground work of the LTSA was needed to suppor this discovery. The second effort, a program to image the Galactic bulge in F220W and F555W (V) was unsuccessful because the UV sensitivity of HST was too low.

4. Human Resources

During the course of the grant, two Ph.D. students were supported. Neil Tyson (Ph.D. 1991) and HongSheng Zhao (Ph.D. 1994). Tyson is now Director of the Hayden Planetarium and a Lecturer at Princeton University. Zhao is a postdoctoral scientist at Leiden University. Several undergraduates were involved in research at various times. Roy Gal is now a graduate student in astronomy (and NSF Fellow) at Caltech. Joseph Biello is now a graduate student in astrophysics at the University of Chicago. Kenneth Mighell worked as a postdoctoral scientist, partially supported by this grant. Mighell is now an Associate Scientist at NOAO, and has his own LTSA grant. Andy McWilliam collaborated with the PI on the analysis of the Galactic bulge giants and received the

McClintock Fellowship of the Carnegie Instiution of Washington, and the Pierce Prize of the American Astronomical Society for this work. McWilliam is now a staff member at the Carnegie Observatories.

5. Publications

Listed below are the significant refereed publications supported by the LTSA grant. The PI also gave a number of invited review talks at IAU and other internation symposia, and these are available on request.

"The Luminosity Function of Late-Type Giants in the Bulge of M31," Rich, R.M., and Mould, J.R. 1991,, *AJ*, **101**, 1286.

"Abundance Analysis of Three Red-Giants in the Metal-Poor Globular Cluster NGC 2298," McWilliam, A., Geisler, G. and Rich, R.M. 1992,, *PASP*, **104**, 1193.

"Far Ultraviolet Radiation from Disk Globular Clusters," Rich, R.M., Minnitti, D., and Liebert, J.W. 1993,, *ApJ*, **406**, 489.

"The Stellar Population and Luminosity Function in M31 Inner Disk and Bulge Fields," Rich, R. M., Mould, J. R., and Graham, J. 1993,, *AJ*, **106**, 2252.

"The First Detailed Abundance Analysis of Galactic Bulge K Giants in Baade's Window" McWilliam, A., and Rich, R.M. 1994,, *ApJS*, **91**, 749.

"Stellar Photometry in the Inner Bulge of M31 Using the HST Wide Field Camera" Rich, R.M., and Mighell, K. 1995,, *ApJ*, **439**, 145.

"Hubble Space Telescope Planetary Camera Observations of the Stellar Population near the Nucleus of M33" Mighell, K., and Rich, R. M. 1995,, *AJ*, **110**, 1649.

" Near-coeval formation of the Galactic bulge and halo inferred from globular cluster ages" Ortolani, S., Renzini, A., Gilmozzi, R., Marconi, G., Barbuy, B., Bica, E., & Rich, R. M. 1995,, *Nature*, **377**, 701.